

ACCELERATED ORBITAL EXPANSION AND SECULAR SPIN-DOWN OF THE ACCRETING MILLISECOND PULSAR SAX J1808.4–3658

ALESSANDRO PATRUNO¹, PETER BULT¹, ACHAMVEEDU GOPAKUMAR² JACOB M. HARTMAN^{3,4}, RUDY WIJNANDS¹, MICHIEL VAN DER KLIS¹, DEEPTO CHAKRABARTY⁵

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ABSTRACT

The accreting millisecond pulsar SAX J1808.4–3658 has shown a peculiar orbital evolution in the past with an orbital expansion much faster than expected from standard binary evolutionary scenarios. Previous limits on the pulsar spin frequency derivative during transient accretion outbursts were smaller than predicted by standard magnetic accretion torque theory, while the spin evolution between outbursts was consistent with magnetic dipole spin-down. In this paper we present the results of a coherent timing analysis of the 2011 outburst observed by the *Rossi X-ray Timing Explorer* and extend our previous long-term measurements of the orbital and spin evolution over a baseline of thirteen years. We find that the expansion of the 2 hr orbit is accelerating at a rate $\dot{P}_b \simeq 1.6 \times 10^{-20} \text{ s s}^{-2}$ and we interpret this as the effect of short-term angular momentum exchange between the mass donor and the orbit. The gravitational quadrupole coupling due to variations in the oblateness of the companion can be a viable mechanism for explaining the observations. No significant spin frequency derivatives are detected during the 2011 outburst ($|\dot{\nu}| \lesssim 4 \times 10^{-13} \text{ Hz s}^{-1}$) and the long term spin-down remains stable over thirteen years with $\dot{\nu} \simeq -10^{-15} \text{ Hz s}^{-1}$.

Subject headings: binaries: general — stars: individual (SAX J1808.4–3658) — stars: neutron — stars: rotation — X-rays: binaries — X-rays: stars

1. INTRODUCTION

The transient X-ray binary SAX J1808.4–3658 is the first accreting millisecond X-ray pulsar (AMXP) discovered (Wijnands & van der Klis 1998) among the 14 systems currently known. It is also the best sampled AMXP thanks to its relatively short recurrence time (1.6–3.3 yr) and the continuous coverage of the *Rossi X-ray Timing Explorer* (*RXTE*) which has extensively monitored all outbursts since 1998. The presence of pulsations reveal the spin of the accreting pulsar ($\approx 401 \text{ Hz}$) and allow the study of torques that act upon the neutron star. This is particularly valuable because the spin evolution reveals details of the recycling mechanism that transforms a newly born slowly rotating neutron star into a millisecond pulsar via accretion (Alpar et al. 1982; Radhakrishnan & Srinivasan 1982). In our previous works (Hartman et al. 2008; Hartman et al. 2009) we reported upper limits on the spin-up of the pulsar due to accretion torques (during outbursts) with a pulsar spin frequency derivative of $|\dot{\nu}| \lesssim 2.5 \times 10^{-14} \text{ Hz s}^{-1}$. This value is smaller than predicted by accretion theory (Ghosh & Lamb 1979) if the spin frequency of SAX J1808.4–3658 substantially differs from the equilibrium spin frequency at the accretion rate close to the peak of the outburst. The long term spin evolution of the pulsar reveals a constant spin-down of magnitude $-5.5 \pm 1.2 \times 10^{-16} \text{ Hz s}^{-1}$ possibly due to magnetic-dipole radiation

acting during quiescence⁶, for a surface magnetic field of the pulsar $B \simeq 1.5 \times 10^8 \text{ G}$, in line with the expected field strength of millisecond radio pulsars.

SAX J1808.4–3658 is undergoing an unexpectedly fast orbital evolution with the orbital period increasing on a timescale of $\approx 70 \text{ Myr}$ (Hartman et al. 2008; di Salvo et al. 2008). The binary has an orbital period of 2.01 hr (Chakrabarty & Morgan 1998) and the donor star is a $0.05 - 0.1 M_\odot$ brown dwarf (Bildsten & Chakrabarty 2001; Deloye et al. 2008) suggesting that the orbital evolution should be dominated by angular momentum loss via gravitational waves and possibly by magnetic braking (Tauris & van den Heuvel 2006). The timescale of the orbital evolution is, however, too fast to be explained with such a scenario, and non-conservative processes with large mass loss from the system have been invoked (di Salvo et al. 2008; Burderi et al. 2009). Hartman et al. (2008); Hartman et al. (2009) suggested instead that interchanges of angular momentum between the companion and the orbit can dominate the short-term orbital evolution as seen in several binary millisecond pulsars (Arzoumanian et al. 1994; Nice et al. 2000).

On October 31 2011 *Swift*-BAT detected a new outburst of SAX J1808.4–3658 (Markwardt et al. 2011; Papitto et al. 2011). This is the 7th outburst observed since its discovery (in 't Zand et al. 1998) and the 6th monitored with *RXTE*. We present a coherent pulsation analysis of the outburst and we complete the study of the spin and orbital evolution of SAX J1808.4–3658 over a baseline of thirteen yr.

2. X-RAY OBSERVATIONS AND COHERENT ANALYSIS

⁶ In the abstract of Hartman et al. 2009 a wrong value of $-5.5 \pm 1.2 \times 10^{-18} \text{ Hz s}^{-1}$ is reported, due to a typographical error.

¹ Astronomical Institute “Anton Pannekoek,” University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands

² Department of Astronomy and Astrophysics, Tata Institute of Fundamental Research, Colaba, Mumbai-400 005, India

³ NASA Postdoctoral Program fellow

⁴ Jet Propulsion Laboratory, Pasadena, CA 91109, USA

⁵ Department of Physics and Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

We use all *RXTE* Proportional Counter Array (PCA; Jahoda et al. 2006) public data for the 2011 outburst (Program-Id 96027). We construct the 2–16 keV X-ray light-curve with PCA Standard2 data averaging the flux for each observation and normalizing it in Crab units (see for example van Straaten et al. 2003). One burst is detected at MJD 55873.9 and all data with a flux more than twice the pre burst level are removed from the light-curve.

For the timing analysis we use all photons (excluding the burst interval) in the energy band $\approx 2 - 16$ keV (5–37 absolute channels) in Event 122 μ s mode. The data are barycentered with the FTOOL *faxbary* by using the optical position (Hartman et al. 2008) and the JPL DE405 solar system ephemeris. We fold ~ 500 s long data segments in pulse profiles of 32 bins, keeping only those with signal-to-noise $> 3.3\sigma$, giving < 1 false pulse detection for the entire outburst. The S/N is defined as the ratio between the pulse amplitude and its 1σ statistical error. The folding procedure uses the preliminary ephemeris reported in Papitto et al. (2011). A fundamental (ν) and a first overtone (2ν) are detected in the pulse profiles. The TOAs are measured separately for each harmonic to avoid that pulse shape variability affects the fiducial point defining the pulse TOA (see Hartman et al. 2008 for details).

To follow the evolution of the orbit and the pulsar spin we fit separately the two sets of TOAs (fundamental and first overtone) with the software TEMPO2 (Hobbs et al. 2006). The initial model used is a Keplerian circular orbit and a constant pulse frequency. We then repeat the folding procedure with the new timing solution until we reach convergence to the final orbital and pulse parameters. To calculate the errors on the rotational parameters we use Monte Carlo (MC) simulations, that account for the presence of long-timescale correlations in the pulse TOAs (Hartman et al. 2008; Arzoumanian et al. 1994). To verify the presence of a spin frequency derivative we fit a pulse frequency and its time derivative to the TOAs and run 10^4 MC simulations to estimate the significance of the measurements (see Hartman et al. 2008 and Patruno et al. (2009a) for further details).

3. RESULTS OF THE 2011 OUTBURST

3.1. X-ray Light-curve and Pulse Profiles

The first *RXTE* pointed observation was taken on November 4, ≈ 5 days after the beginning of the outburst (Markwardt et al. 2011). The X-ray flux shows a peak at ≈ 80 mCrab, remarkably higher than the peak luminosity in 2005 and 2008 and similar to the 1998 and 2002 values (Wijnands 2004). Since the observations started 5 days after the onset of the outburst, the true outburst peak at MJD 55868 (observed by *Swift*-BAT) has been missed by *RXTE*. The *RXTE* PCA light-curve of the 2011 outburst is shown in Figure 1.

The flux is observed to slowly decay over the entire duration of the main outburst, reaching a minimum flux of 8 mCrab on MJD 55880. The flux then keeps decreasing with two bumps at MJD 55881 and 55884, which might possibly be associated with the flaring-tail stage, when quasi periodic bumps are observed at low flux level (Wijnands et al. 2001; Hartman et al. 2008; Patruno et al. 2009b). However, differently from the 2000 to 2008 outbursts, this phase is poorly sam-

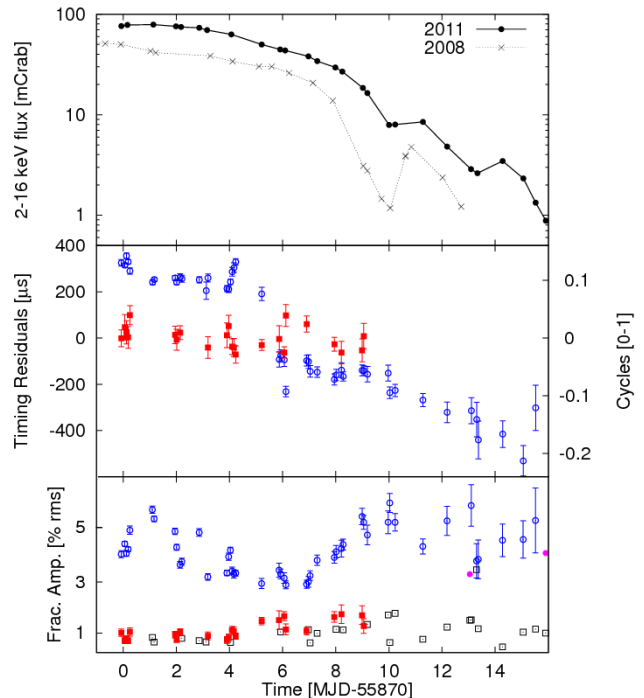


FIG. 1.— **Top panel:** X-ray light-curve (2–16 keV) of the 2011 outburst (solid line) compared to the 2008 outburst (dotted curve). The data points are *RXTE* observations-long averages. **Middle Panel:** timing residuals for fundamental (blue dots) and first overtone (red squares) for a $\nu = \text{const}$ model. Each data point is an *RXTE* orbit-long average. The fundamental has a jump of ~ 0.15 at MJD ≈ 55875 . **Bottom Panel:** Fractional amplitude of the fundamental (blue dots) and first overtone (red squares). The 95% c.l. upper limits are indicated with pink circles (fundamental) and black open squares (first overtone).

pled and difficult to characterize. During the tail a strong 1 Hz modulation was reported for several outbursts (2000, 2002, 2005; van der Klis et al. 2000; Patruno et al. 2009b) but it is not detected in any of the 2011 observations.

The source became undetectable on MJD 55885.9 (November 20) and the monitoring abruptly ended on November 27, due to solar constraints. These also prevented to establish whether at the time of the last observation SAX J1808.4–3658 was in quiescence or in one of the faint ($\sim 10^{32}$ erg s $^{-1}$) states observed in the past with *Swift* and *XMM-Newton* observations (Wijnands 2003; Campana et al. 2008).

The pulse profiles are very sinusoidal until MJD 55874 and then change becoming skewed with a more evident first overtone peaking on the right part of the profile. At MJD 55880, during the possible flaring stage, the pulse profiles become very sinusoidal again, a phenomenon never observed in the previous outbursts. This is reflected in the rms amplitude of the two harmonics (see Fig 1).

3.2. Timing Noise and Error Estimation

The timing solution of the 2011 outburst is displayed in Table 1 while a previous analysis of the five outbursts observed with *RXTE* is available in Hartman et al. (2008); Hartman et al. (2009). The authors found strong timing noise operating on the same timescales over which the pulse frequency and its time derivative were measured.

TABLE 1
SAX J1808.4–3658 TIMING SOLUTION FOR THE 2011 OUTBURST

Parameter	Value	Stat. Error	Syst. Error
ν [Hz]	400.97520981	7×10^{-8}	10^{-7}
$ \dot{\nu} $ [Hz s $^{-1}$]	$< 4 \times 10^{-13}$	(95% c.l.)	
P_b [s]	7249.162	0.003	
$A_x \sin(i)$ [lt-ms]	62.798	0.005	
T_{asc} [MJD]	55896.895635	0.00002	
e	$< 10^{-4}$	(95% c.l.)	

The 2011 TOA residuals of a $\nu = \text{const}$ model, show the typical behavior observed in the previous outbursts in both harmonics.

We detect a strong phase jump in the fundamental with magnitude of 0.15 cycles (0.3 ms) at MJD $\approx 55874 - 55876$. This behaviour is similar to what was previously seen during the 2002 and 2005 outbursts, with phase jumps of 0.2 cycles observed when the flux reached the transition from slow to fast decay (Burderi et al. 2006, Hartman et al. 2008, Patruno et al. 2009b). The first overtone instead has no phase jump but displays a short timescale (few minutes to ~ 1 day) scattering slightly in excess of that expected from measurement errors alone.

We use the phase information of the first overtone to phase connect across the phase jump of the fundamental (see Hartman et al. 2008 for details of the procedure). A net spin frequency derivative (i.e., measured over the entire outburst length) is not detected, with upper limits of $|\dot{\nu}| \lesssim 8.8 \times 10^{-13} \text{ Hz s}^{-1}$ at the 95% confidence level. By removing the TOAs of the first observation in both harmonics (when timing noise is strong) and the 0.15 cycle phase jump for the fundamental, we obtain similar results with a more stringent constraint on the spin frequency derivative: $|\dot{\nu}| \lesssim 4 \times 10^{-13} \text{ Hz s}^{-1}$ (95% c.l.).

The errors on the orbital parameters measured with the fundamental are only marginally affected by timing noise since they are measured on timescales (2 hr) different than the timing noise one (\sim days). This is verified by calculating a power spectrum of the TOA residuals and comparing the Poissonian level to the power at the orbital frequency $1/P_b$. The excess power at $1/P_b$ is about 1.5 and 3 times the Poissonian level for fundamental and first overtone respectively. We therefore rescale the statistical errors on the orbital parameters by the same factor.

3.3. X-ray Flux - Pulse Phase Correlation

In 2009 (Patruno et al. 2009c) proposed an alternative method to partially account for the timing noise in the TOAs of AMXPs. X-ray flux variations were found to be linearly correlated or anti-correlated with the pulse phases. Instead of minimizing the rms of the TOA residuals, Patruno et al. (2009c) minimized the χ^2 of a linear fit to the phase-flux correlation, finding slightly different spin frequencies than those measured with rms minimization methods. The reason of this difference is that instead of treating timing noise as a red noise process of unknown origin, the variations of the X-ray flux are assumed to instantaneously affect the pulse phases. We found that while the fundamental frequency always follows a correlation, the first overtone in some cases behaves differently and we exclude it from our 2011 analysis. By repeating the same procedure out-

lined in Patruno et al. (2009c) for the 2011 outburst, we find a pulse frequency of $\nu = 400.97520981(7) \text{ Hz}$, where 1σ errors have been rescaled by a factor 2.5 such that $\chi^2/\text{dof} = 1$ (Bevington & Robinson 2003; Patruno et al. 2009d). The difference between this value and the pulse frequency ν_{rms} obtained with standard rms minimization of the TOA residuals is $\nu - \nu_{rms} = -0.15 \pm 0.08 \mu \text{ Hz}$.

4. RESULTS ON THE LONG TERM EVOLUTION OF SAX J1808.4-3658

4.1. Long Term Spin Frequency Evolution

We first fit the change of the six constant pulse frequencies (from 1998 to 2011) of SAX J1808.4–3658 using the values reported in Patruno et al. (2009c) and the 2011 frequency obtained from the flux-phase correlation technique. We rescale the errors of each spin frequency to give a $\chi^2/\text{dof} = 1$ and we fit a linear relation to the data. The fit gives a $\chi^2 = 5.4$ for 4 dof, and a spin-down of $\dot{\nu} = -1.65(20) \times 10^{-15} \text{ Hz s}^{-1}$ (Fig. 2). This is in agreement with the value reported in Patruno et al. (2009c). A spin frequency second derivative is not required by the fit, and we can place upper limits of $|\ddot{\nu}| \lesssim 10^{-24} \text{ Hz s}^{-2}$ (95% c.l.).

We also fit the 2011 outburst pulse frequency with the rms minimization method (i.e., TEMPO2 plus MC errors), together with the previous five spin frequency measurements obtained with the same technique (Hartman et al. 2009). The χ^2 is high, 19.5 for 4 dof and we ascribe this almost exclusively to the 2000 outburst spin frequency (see Hartman et al. (2009)). If we remove the 2000 data, the fit returns a $\chi^2 = 3.57$ for 3 dof. The spin-down is constrained to be $\dot{\nu} = -7.4(4) \times 10^{-16} \text{ Hz s}^{-1}$. This estimate is within 2σ from the value previously reported by Hartman et al. (2009) and within 1σ when removing the 2000 outburst data.

Since both fits of the long-term spin frequency evolution are statistically acceptable, we cannot decide which of the two values reported is closer to the true $\dot{\nu}$. The differences in the ν and long term $\dot{\nu}$ found with the rms minimization and with the phase-flux correlation reflect a systematic uncertainty of $\sim 0.1 \mu \text{ Hz}$ that needs to be considered until the exact mechanism behind timing noise is identified.

4.2. Orbital Evolution

To detect variations of the orbital period we use the procedure explained in Hartman et al. (2008); Hartman et al. (2009) that requires estimates for the times of passage through the ascending node T_{asc} at various outbursts. We choose as a reference point the $T_{asc,ref}$ value in Table 1 of Hartman et al. (2009), and we calculate the residuals $\Delta T_{asc} = T_{asc,i} - (T_{asc,ref} + N P_b)$, where $T_{asc,i}$ is the i -th outburst and N is the closest integer to $(T_{asc,i} - T_{asc,ref})/P_b$. The chosen P_b is also reported in Table 1 of Hartman et al. (2009).

In a previous work (Hartman et al. 2008; Hartman et al. 2009) we detected a $\dot{P}_b = (3.80 \pm 0.06) \times 10^{-12} \text{ s s}^{-1}$ (see also di Salvo et al. 2008 and Burderi et al. 2009). When including the 2011 data, a parabolic fit gives a $\chi^2 = 62.8$ for 3 dof, thus suggesting that a constant increase of the orbital period is not the correct model for SAX J1808.4–3658. We then add an orbital period second derivative (\ddot{P}_b) and

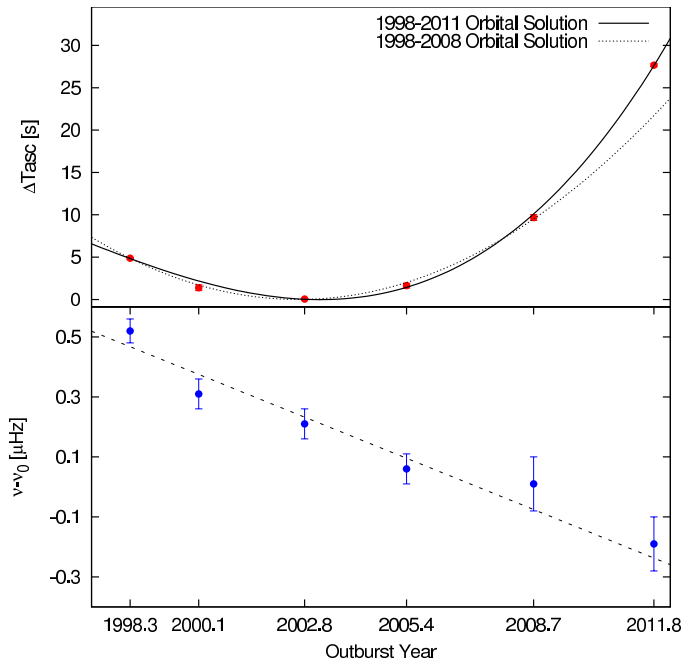


FIG. 2.— Orbital (top panel) and spin frequency evolution (bottom panel) over 13 years of observations. The T_{asc} residuals cannot be fitted with a parabola (dotted line) and they need a cubic fit suggesting an acceleration of the orbital period $\ddot{P}_b = 1.65 \times 10^{-20} \text{ s s}^{-2}$. The spin-down of the pulsar is stable and proceeds at a rate of $-10^{-15} \text{ Hz s}^{-1}$. The reference frequency is $\nu_0 = 400.975210 \text{ Hz}$.

fit a cubic polynomial to the data. The fit is statistically acceptable, with $\chi^2 = 5.4$ for 2 dof and parameters $\dot{P}_b = 3.5(2) \times 10^{-12} \text{ s s}^{-1}$ and $\ddot{P}_b = 1.65(35) \times 10^{-20} \text{ s s}^{-2}$ (see Figure 2).

A third time derivative or a sinusoidal model are not required by the data. We also tried to fix the P_b and \dot{P}_b at the values observed up to 2008 and add a sinusoidal fit to the data to investigate the possibility of apsidal motion. The fit is statistically unacceptable and the periodicity found is of the order of 10^3 yr , which is already orders of magnitude larger than the expected general relativistic effect alone.

5. DISCUSSION

5.1. Pulsar Spin Evolution

The long term spin-down continues with a constant rate comparable to what has been measured between 1998 and 2008. The only plausible explanation for the spin-down in SAX J1808.4–3658 requires magnetic-dipole radiation with a surface magnetic field of the neutron star at the poles $B \approx (1.5 - 2.5) \times 10^8 \text{ G}$ (for a radius $R = 10 \text{ km}$) for a magnetic-dipole moment $\mu = (0.7 - 1.5) \times 10^{26} \text{ G cm}^3$. This range includes the different spin-down measurement methods reported in § 3.2 and § 3.3 and is close to the B field obtained with Fe line spectral fitting (Cackett et al. 2009; Papitto et al. 2009) and accretion disk modeling (Ibragimov & Poutanen 2009).

The remarkably constant long term spin-down places stringent constraints on any ongoing spin-up during an outburst. If spin frequency variations were larger than the upper limit reported by Hartman et al. (2008) ($|\dot{\nu}| \lesssim 2.5 \times 10^{-14} \text{ Hz s}^{-1}$), they would produce a scatter in the observed spin frequencies of the order of $0.1 - 0.4 \mu \text{ Hz}$ (for

$\dot{\nu} \sim 5 - 10 \times 10^{-14} \text{ Hz s}^{-1}$). This scatter is not observed with statistical errors of $\approx 0.05 - 0.1 \mu \text{ Hz}$ (see Fig 2), and suggests that the net spin-up during an outburst is at best very small in magnitude for SAX J1808.4–3658.

5.2. Orbital Period Evolution

The orbital period P_b indicates that the orbit of SAX J1808.4–3658 is expanding and accelerating at a very fast rate. The timescale for the acceleration is:

$$\tau_{acc} \cong \frac{2\dot{P}_b}{\ddot{P}_b} \sim 10 \text{ yr} \quad (1)$$

suggesting that the identified \dot{P}_b might not represent the secular evolution of the orbital period. If we assume that the measured acceleration is constant, then SAX J1808.4–3658 has changed sign of \dot{P}_b about 25 years ago. There is, however, no reason for \dot{P}_b to be constant, since we are not sensitive to higher order derivatives and both \dot{P}_b and \ddot{P}_b might be part of long timescale variations similar to those observed in binary millisecond pulsars (Nice et al. 2000). Until the 2008 outburst, when only a constant \dot{P}_b was detected, two interpretations were given: a secular orbital evolution due to non-conservative mass transfer (di Salvo et al. 2008; Burderi et al. 2009) and a short-term evolution associated with exchange of angular momentum between the donor star and the orbit (Hartman et al. 2008; Hartman et al. 2009).

If SAX J1808.4–3658 has increased its mass loss due to an enhancement of the donor ablation, then the wind loss from the companion (\dot{M}_w) needs to increase at a rate comparable with that of the orbital period, since $\dot{P}_b \propto \dot{M}_w$. The mass loss is related to $\dot{E}_{abl} = 0.25 (R/A)^2 \dot{E}$, where \dot{E}_{abl} is the ablation power, \dot{E} is the pulsar rotational spin-down power and R and A the donor radius and the semi-major axis of the binary. To explain the acceleration \ddot{P}_b , the energy loss of the pulsar \dot{E} needs to have increased (in absolute value) in the last 13 years by a factor of ≈ 5 . Since $\dot{E} \propto \nu \dot{\nu}$, the spin-down $\dot{\nu}$ needs to vary at a rate $\ddot{\nu} \simeq -10^{-23} \text{ Hz s}^{-2}$ to reach the energy loss required. By using the long-term spin evolution presented in the previous section we can put constraints on $|\ddot{\nu}| \lesssim 10^{-24} \text{ Hz s}^{-2}$. We conclude that the enhanced ablation scenario is not supported by the observations.

A dynamically induced period derivative in the gravitational potential well of a third body can also be excluded. The effect of a potential well is identical on the orbital and spin frequencies and derivatives:

$$f^{(n)} = -f \frac{\mathbf{a}^{(n-1)} \cdot \hat{\mathbf{n}}}{c} \quad (2)$$

where $f^{(n)}$ is the n -th time derivative of the orbital or spin frequency, \mathbf{a} is the acceleration due to the third body, $\hat{\mathbf{n}}$ is a unit vector along the line of sight and c the speed of light. To explain the observed \ddot{P}_b we need $\ddot{\mathbf{a}} \sim 10^{-15} - 10^{-16} \text{ m s}^{-3}$ and $|\ddot{\nu}| \sim 10^{-21} \text{ Hz s}^{-1}$, which is not observed.

If the measured orbital evolution is a short-term event, then one explanation can be found with the donor spin-orbit coupling model. A coupling between the pulsar rotational energy loss (in form of winds or fields) and the orbital angular momentum (Damour & Taylor

1991) is ruled out by the small magnitude of the effect produced by the tiny \dot{E} of SAX J1808.4–3658. A mass quadrupole variation of the donor star is a more promising possibility. A change ΔQ in the mass quadrupole leads to a change in orbital period (Richman et al. 1994; Applegate & Shaham 1994; Applegate & Patterson 1987):

$$\frac{\Delta P_b}{P_b} = -2 \left(\frac{R}{A} \right)^2 \frac{\Omega^2 R^3}{GM} \frac{M_s}{M} \frac{\Delta \Omega}{\Omega} \quad (3)$$

where M and R are the donor mass and radius, M_s is a thin shell of mass generating the quadrupole, and Ω the angular velocity of the star. If we assume that the angular velocity of the donor is almost synchronous with the orbital angular velocity, then the variation $\Delta P_b \simeq 0.004$ s observed in the last 13 years gives:

$$\frac{\Delta \Omega}{\Omega} \sim 10^{-4} \frac{M}{M_s} \quad (4)$$

The observed orbital period variations in the eclipsing millisecond pulsar PSR J2051-0827 and PSR B1957+20 are likely to be caused by changes in the quadrupole moment of the companion (Arzoumanian et al.

1994; Doroshenko et al. 2001; Lazaridis et al. 2011). Applegate (1992) proposed a magnetic activity cycle that leads to a deformation of the star at the origin of this behavior. The donor star of SAX J1808.4–3658 is also in Roche lobe contact, whereas binary millisecond pulsars are detached systems. If the orbital period of SAX J1808.4–3658 has decreased in the past for some time, then the Roche lobe has moved across the outer envelope of the brown dwarf enhancing the mass transfer rate. A detailed discussion of this effect is beyond the scope of this letter, but we can speculate that SAX J1808.4–3658 has gone through periodic episodes (each lasting $\tau_{acc} \sim 10$ yr) of enhanced accretion in the past. This effect is opposite during the accelerated orbital expansion, with the mass transfer being less than in the non-accelerated case. The quadrupolar moment change has also the effect of heating the star, providing an explanation for the large entropy content of the donor (Deloye et al. 2008).

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